

# The Combustion Product Monitor Instrument for the Spacecraft Fire Safety Demonstration Project

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The Combustion Product Monitor (CPM) instrument is a six-channel tunable laser absorption spectrometer capable of measuring ambient gas-phase concentrations of CO, HCl, HCN, HF, CO<sub>2</sub>, and O<sub>2</sub> in spacecraft environments. Monitoring of these compounds can provide early warning detection of combustion events and can also facilitate safe post-fire cleanup. Here, we will describe the development of a CPM instrument optimized for operation as part of the Spacecraft Fire Safety Demonstration (Saffire) Project. As part of Saffire, the CPM instrument will measure concentrations of the target gases during low-gravity, reduced-pressure oxidative pyrolysis of relevant test materials aboard a transfer vehicle returning from low Earth orbit. We will describe the CPM instrument design, absorption line selection, theoretical and experimental detection limits, and environmental testing.

## Nomenclature

CPM	= combustion product monitor (instrument)
Saffire	= spacecraft fire safety demonstration
ISS	= international space station
TLAS	= tunable laser absorption spectrometer
CDM	= carbon dioxide monitor
NDIR	= non-dispersive infrared (detection)
CO	= carbon monoxide
CO <sub>2</sub>	= carbon dioxide
O <sub>2</sub>	= oxygen (gas)
HCN	= hydrogen cyanide (gas)
HCl	= hydrogen chloride (gas)
HF	= hydrogen fluoride (gas)
N <sub>2</sub>	= nitrogen (gas)
SMAC	= Spacecraft Maximum Allowable Concentration
IR	= Infrared
H <sub>2</sub> O	= water (vapor)
ppmv	= part per million (by volume)
FPGA	= field-programmable gate array
2f	= second harmonic (detection)
DC	= direct current
DFB	= distributed feedback (laser)
QC	= quantum cascade (laser)
IC	= interband cascade (laser)
atm	= atmospheric (pressure)
TEC	= thermoelectric cooler

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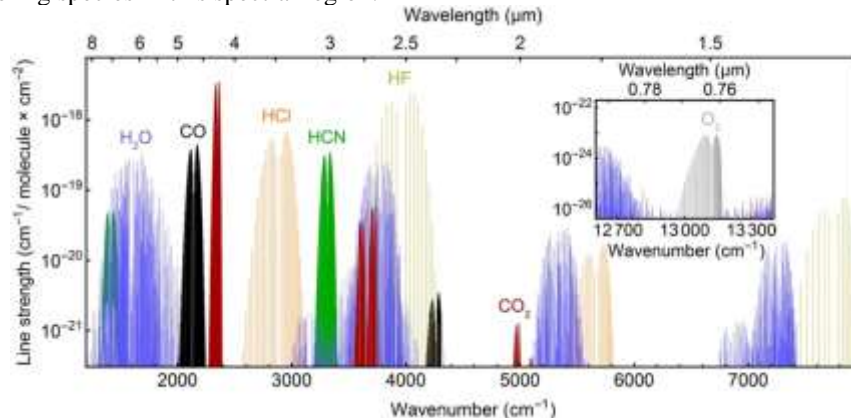
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## I. Introduction

With the recent interest in longer durations and greater distances from Earth for future human spaceflight missions, spacecraft safety systems will play a crucial role in keeping the crew safe and healthy, and must be capable of long-term accuracy and maintenance-free operation. Monitoring of combustion products is important for early detection of accidental fires as well as evaluation of air quality following a fire event<sup>1, 2</sup>. Even though most materials used on the inside of crewed spacecraft have low flammability, they can generate smoke by oxidative pyrolysis<sup>3</sup>. Therefore, smoke detectors aboard the spacecraft must detect gases that are generated or consumed during oxidative pyrolysis of various polymers. Currently, electrochemical sensors (Industrial Scientific CSA-CP) are used on the International Space Station for monitoring CO, O<sub>2</sub>, HCl, and HCN, and CO<sub>2</sub> monitoring (CDM) is based on non-dispersive infrared (NDIR) detection<sup>4</sup>. These sensors have the advantages of being portable and consuming little power; however, maintenance and calibration are required periodically, and the sensors generally cannot withstand exposure to vacuum, and the calibration of CDM over a wide range of pressure is challenging. Tunable laser absorption spectroscopy (TLAS) sensors have shown operation for thousands of hours without maintenance or calibration<sup>5</sup>, with detection of selected gases at low concentration over a wide range of total pressure<sup>6, 7</sup>, and are capable of withstanding exposure to vacuum, making them a promising candidate to be used for smoke detection and air quality monitoring aboard spacecraft.

In the past few years, we have developed and reported on the testing of a CO TLAS sensor<sup>8</sup> and of a five-channel TLAS sensor capable of monitoring the concentrations of CO, HCl, HCN, HF, and CO<sub>2</sub> continuously<sup>9</sup>. These sensors have shown to achieve detection of these molecules at low-level limits below the standard Spacecraft Maximum Allowable Concentrations (SMACs) and achieve detection over a large dynamic range of pressure, temperature, and molecules concentrations<sup>10</sup>. Due to the very strong fundamental vibrational absorption of target molecules in the mid-infrared (IR) spectral region, these sensors used a single-mode mid-IR laser for each of the target molecules in order to allow for the use of a compact absorption cell. Each laser wavelength was selected carefully in order to overlap a strong absorption line of the molecule of interest while avoiding absorption of other gases that might be present in human spacecraft environments. Following this first development effort, a sensor allowing the detection of the five gases previously mentioned and O<sub>2</sub> was reported in Ref. 14. Figure 1 shows the absorption line strength of the different targeted molecules in the spectral region of interest. Absorption lines of water (H<sub>2</sub>O) vapor are also shown, since this is the main interfering species in this spectral region.

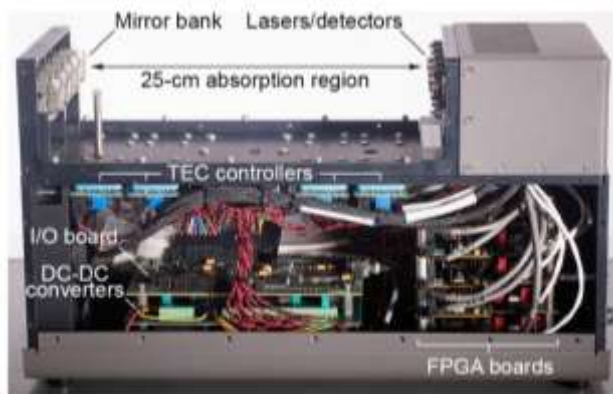


**Figure 1. Absorption lines of H<sub>2</sub>O and the six gases targeted by the TLAS combustion product sensor in the near- to mid-infrared wavelength range. (Line strengths were obtained from the HITRAN Database.)**

Here, we describe the absorption line selection and instrument design, theoretical and experimental detection limits, and environmental testing of the Combustion Product Monitor (CPM) instrument developed for the Spacecraft Fire Safety Demonstration (Saffire) experiment. Saffire is a series of experiments established to investigate large-scale flame growth and material flammability limits in space. It consists of six low-gravity fire experiments on re-supply vehicles (Cygnus) returning from the International Space Station (ISS) once it has completed its primary supply mission. The data from these experiments will enable spacecraft designers and safety engineers to understand spacecraft fire events at relevant length and time scales and provide data for the verification of numerical models<sup>11</sup>. We focus specifically on the design of the optical head that was based on requirements for minimum detection levels of the six target gases as well as findings from prototype instruments, and the performance of the soon-to-be-flown TLAS instrument aboard a Cygnus capsule where the Saffire experiment will be performed.

## II. Instrument Design

In order to achieve measurements of the targeted molecules in the environment of interest, we have opted for an open-cell configuration where the surrounding atmosphere is sampled at the same pressure and temperature as the surrounding environment. This configuration was tested with a first prototype shown in Fig. 2 and was capable of detecting 5 molecules simultaneously; CO, HCl, HCN, HF, and CO<sub>2</sub>. This instrument was built using five lasers and detectors, mounted onto the same heat-sink assembly, and five mirrors 25 cm away from the lasers/detectors in order to form a 50 cm optical path. The emission wavelength of each laser was tuned over the absorption line with a current scan at a 200 ms period. Each of the lasers was controlled by a dedicated FPGA board that supplied the current and recorded the corresponding detector response. This system was based on the second-harmonic (2f) absorption spectroscopy method<sup>12</sup> where a sinusoidal current modulation is applied to the laser, at 5 kHz in our case, in addition to the linear current ramp, and the detector signal is demodulated at twice the modulation frequency. Both 2f and direct (DC) detector response were measured. While this instrument showed performance to meeting our targets for a CPM instrument, the electronics were bulky due to the use of individual FPGA for each laser/detector, and the optical head design required a relatively large absorption region. A compact prototype was developed where the size of the electronics compartment was reduced using a single microcontroller allowing the combination of the FPGA boards into a single board with similar functionalities. Furthermore, a 10-cm optical path was used for measuring CO, HCl, HCN, HF, and CO<sub>2</sub>, as well as the addition of the detection of O<sub>2</sub>. While the acid gases and CO were detected using a single 10-cm pass, CO<sub>2</sub> and O<sub>2</sub> used a multi-pass cell based on Herriott mirrors<sup>13</sup> in order to reach an effective pathlength of 1.7 m. This instrument is described in Ref. 14.

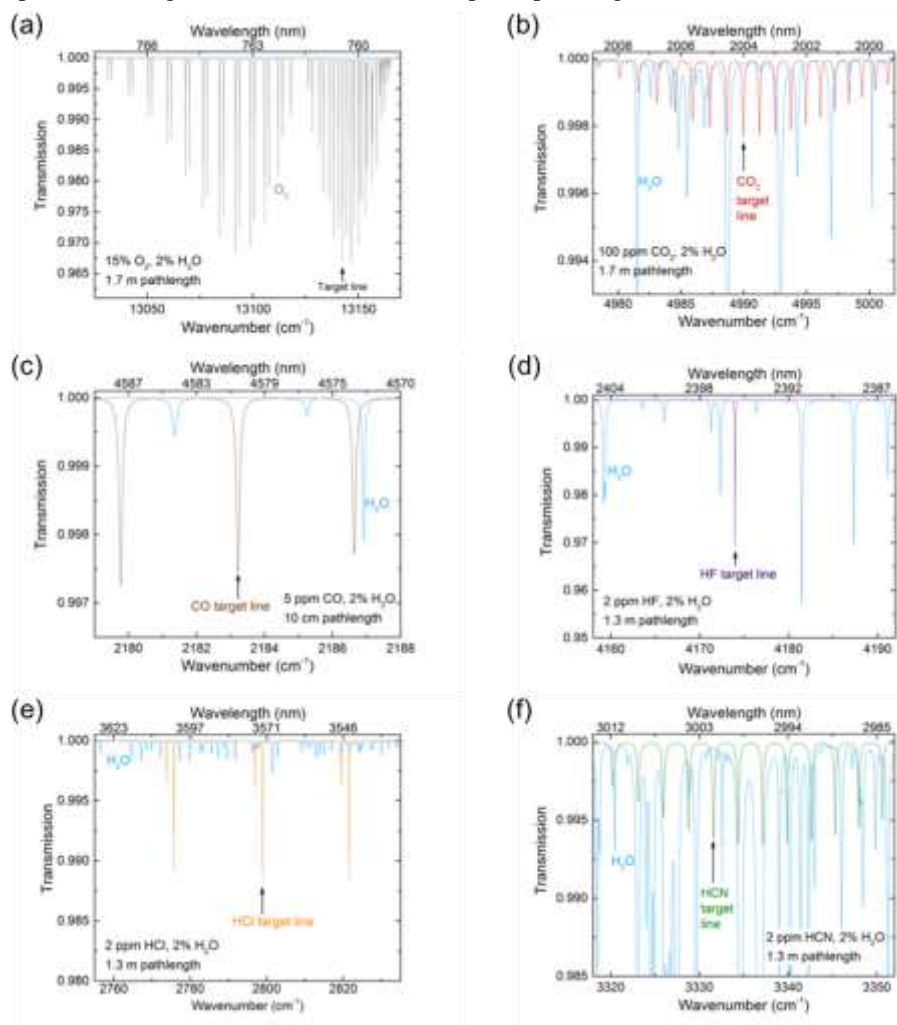


**Figure 2. Photograph of the first-generation five-channel TLAS instrument capable of measuring simultaneously CO, HCl, HCN, HF, and CO<sub>2</sub> with a two-pass 50 cm long optical path. This instrument was described in details in Ref. 9.**

Based on this prototype that used a minimal pathlength for a reduced optical head area, as well as a compact electronics design, we showed that while it was possible to reach a relative line-center absorption at minimum detection on the order of  $10^{-4}$ , the use of free-space optics and having collimating lenses outside of the laser packages for most wavelengths made reaching accuracy requirements and minimum detection level challenging due to the incorporation of interference fringes, with the addition of short sampling and averaging time (1 second), and no interference fringes washing schemes. The minimum value was considered to be the value at which the 2f signal of the target molecule was above the noise, remained well distinct above any noise drift, and remained stable, meaning that the 2f amplitude wasn't impacted by any noise variations. Thus, we developed a modified CPM instrument targeting a relative line-center absorption at minimum detection on the order of  $10^{-3}$ . Using the HITRAN Database, we investigated the selection of the appropriate mid-infrared lines for CO, HCl, HCN, and HF, and near-IR lines for CO<sub>2</sub> and O<sub>2</sub>. It is important to verify that these lines are all clear of absorption interference from other gases, particularly H<sub>2</sub>O, as well as having a sufficient pathlength to reach a relative line-center absorption at minimum detection on the order of  $10^{-3}$ . The minimum detection limits were based on the SMACs<sup>10</sup>, where a detection limit corresponding to or below the 24 h exposure level was targeted as being our required minimum detection, as well as toxicity requirements provided by NASA.

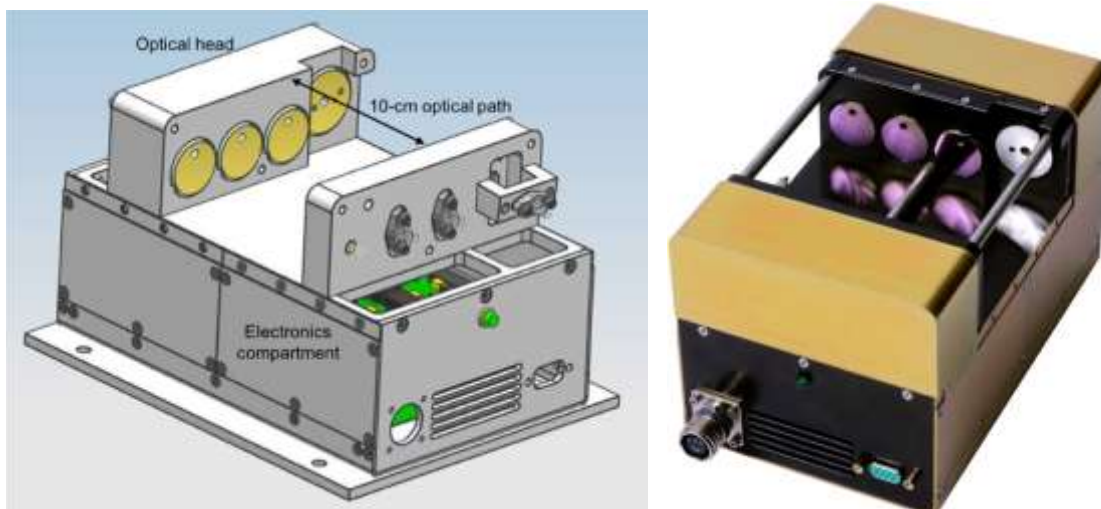
The different targeted absorption lines are shown in Fig. 3 at 300 K and atmospheric pressure for their minimum detection limits with an optical pathlength giving a relative line-center absorption at minimum detection on the order of  $10^{-3}$ . The minimum detection for O<sub>2</sub> is 15%, corresponding to the minimum limit of a habitable environment, with an absolute accuracy of 1% or better. Strong absorption lines corresponding to electronic transitions of O<sub>2</sub> are found near 760 nm wavelength, Fig. 3 (a), and an optical pathlength of 1.7 m allows for the detection of O<sub>2</sub> within the required accuracy. For CO, the minimum detection limit is 5 ppm with an accuracy of  $\pm 10\%$ , well below the SMAC 24 h maximum exposure limit of 100 ppm. This is due to the important role that CO plays in fire-related hazards and the detection of this molecule at low concentration can be an early indicator of such hazards. Strong absorption lines near 4600 nm wavelength, Fig. 3 (c), enable achieving this minimum detection limit with an optical pathlength of 10 cm. In order to monitor accurately CO<sub>2</sub> variation in typical environment, the targeted minimum detection was 100

ppmv with an accuracy of  $\pm 10\%$ , and this can be obtained by using absorption lines near 2004 nm, Fig. 3 (b), and an optical pathlength of 1.7 m. Finally, for the three targeted acid gases, HF, HCl, and HCN, we target a minimum detection requirement of 2 ppmv with an accuracy of  $\pm 25\%$ . Measuring these concentrations is possible with the use of mid-IR absorption lines, Fig. 3 (d), (e), and (f), and an optical pathlength of 1.3 m for each individual laser channel.



**Figure 3. Calculated transmission spectra for the six gases targeted by the TLAS CPM sensor used for the Saffire experiment. The spectra were calculated using the HITRAN Database at a standard temperature and pressure of 300 K and 1 atm and with the indicated pathlengths. Since H<sub>2</sub>O is the primary interfering gas present in the environment of interest, water vapor transmission spectra are also plotted around the target absorption wavelength of each molecule.**

With the objective of developing a compact TLAS sensor, a multi-pass cell is used for all channels at the exception of CO, where a single direct pass is sufficient. This configuration allows us to keep the 10 cm optical path from the previous prototype, minimizing the length of the optical head. For the detection of CO<sub>2</sub> and O<sub>2</sub>, the CPM uses near-IR lasers coupled into a single-mode fiber mated to small-diameter collimating lenses. This allows the use of a single pair of Herriott mirrors that supports multi-passes for the CO<sub>2</sub> and O<sub>2</sub> channels in an offset beam pattern, with a hole in the center of the mirrors for the CO channel, thus minimizing the total width of the sensor. The lasers used to detect the three acid gases are free-space mid-IR lasers with each beam collimated and injected into an individual multi-pass cell using Herriott mirrors with 1.3 m of total optical pathlength for each channel. An illustration of the instrument is shown in Fig. 4, where the electronics design is similar to Ref. 12. Each channel was averaged over a 1 second timeframe. Furthermore, to avoid corrosion of the instrument due to the presence of acid gases, components have been chosen wisely, have a protective coating when thought necessary, and the electronics is protected with a conformal coating.



**Figure 4. Rendering (left) and photograph (right) of the compact TLAS instrument for the Saffire experiment. The CO channel uses a 10-cm single-path optical path, the HCl, HCN, and HF channels use a 1.3-m multi-pass cell configuration, and the CO<sub>2</sub> and O<sub>2</sub> channels use a multi-pass cell configuration of 1.7-m.**

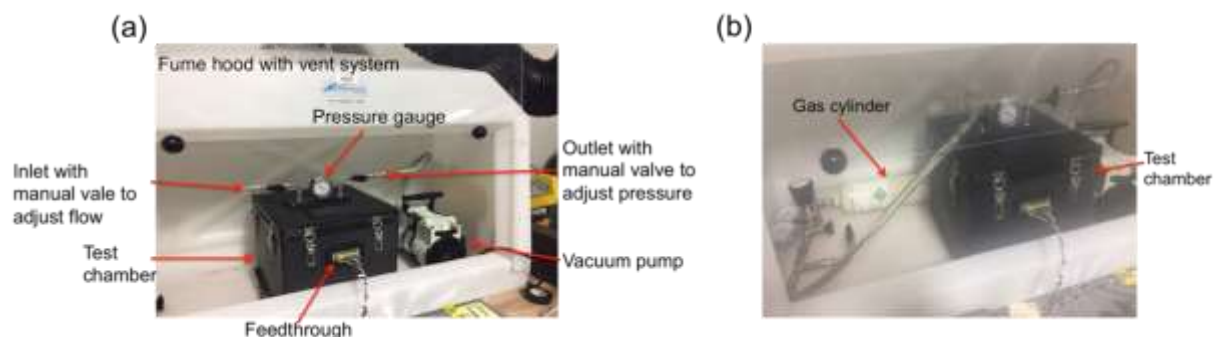
### III. Performance

Performance requirements are shown in Table 1, including the detection range and accuracy for each channel, along with the SMACs, the optical pathlength, and the targeted wavelength and absorption depth from Fig. 3.

**Table 1. Performance targets for the Combustion Product Monitor instrument.**

Compound	Spacecraft Maximum Allowable Concentration (SMACs) [10]	Target Detection Range	Target Accuracy	Optical Pathlength (cm)	Target Wavelength (nm)	Relative line-center absorption at minimum detection level ( $\times 10^{-3}$ )
CO	1 h: 425 ppm 24 h: 100 ppm 7 d: 55 ppm 30+ d: 15 ppm	5 – 1,000 ppmv	$\pm 10\%$	10	4580.4	2.55
HCl	1 h: 5 ppm 24 h: 2 ppm 7 d: 1 ppm 30+ d: 1 ppm	2 – 50 ppmv	$\pm 25\%$	130	3572.8	11.87
HCN	1 h: 8 ppm 24 h: 4 ppm 7 d: 1 ppm 30+ d: 1 ppm	2 – 50 ppmv	$\pm 25\%$	130	3001.5	6.23
HF	1 h: 5 ppm 24 h: 2.5 ppm 7 d: 1 ppm 30+ d: 1 ppm	2 – 50 ppmv	$\pm 25\%$	130	2395.8	31.32
CO <sub>2</sub>	1 h: 2% 24 h: 1.3% 7 d: 0.7% 30+ d: 0.7%	100 – 30,000 ppmv	$\pm 10\%$	170	2004.05	2.3
O <sub>2</sub>	--	15 – 50% (v)	$\pm 1\%$ O <sub>2</sub>	170	760.9	33.8

The compact TLAS CPM instrument as shown in Fig. 4 was calibrated for CO, CO<sub>2</sub>, and O<sub>2</sub> in a custom made vacuum oven, where the pressure and temperature can be set and gases of known concentration for each target molecule are ported to the chamber. Since the acid gases are highly corrosive and would degrade the test chamber, these channels were roughly calibrated using total absorption measurements in an open ventilated configuration, with test gases ported directly to the optical head of the CPM instrument. Performance tests were performed at ZIN Technologies, Cleveland, Ohio, using the setup is shown in Fig. 5 that consists of an acrylic chamber inside a fume hood specially design to handle the use of acid gases. The TLAS CPM instrument was placed inside the chamber with a feedthrough that is used to provide power to the sensor and allow transmission of collected data, and the pressure was controlled using a roughing pump, a cylinder of the gas to be measured or dry nitrogen (N<sub>2</sub>), and a system of valves.



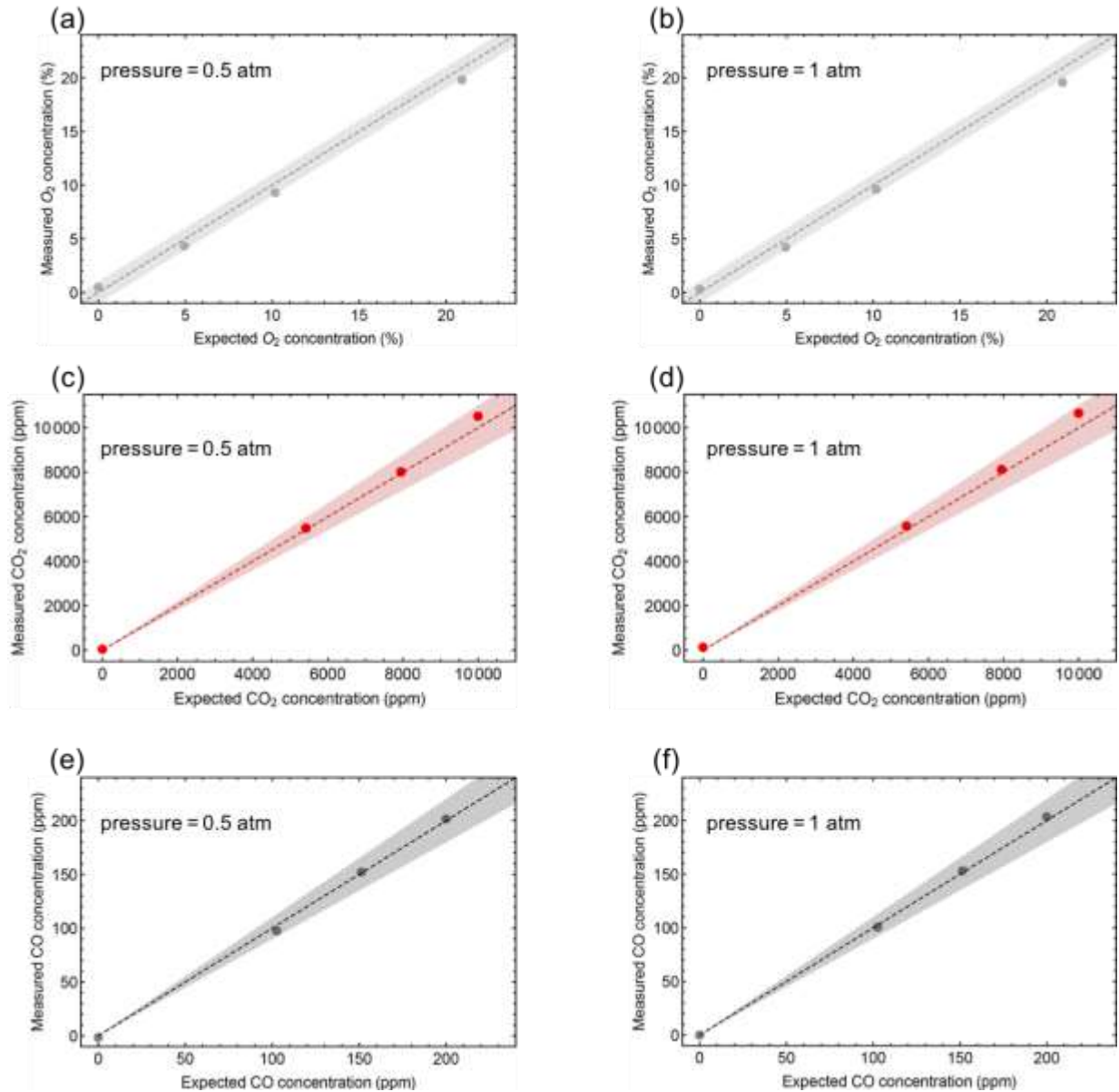
**Figure 5. Test setup used to characterize the TLAS CPM instrument. (a) View of the sealed test chamber inside a fume hood, showing the pump used to control the pressure inside the chamber. (b) Picture of the connections to interface test gas cylinders with the test chamber.**

The measurements were conducted at two nominal pressures; 0.5 atm and 1 atm. For testing of O<sub>2</sub>, CO<sub>2</sub>, and CO, the chamber is first pumped to ~0.5 atm, backfilled with the gas to be sampled to ~1 atm, resulting in 50/50 ratio of air to sampled gas, pumped down to 0.5 atm, backfilled again resulting in 25/75 ratio of air to sampled gas, pumped to ~0.5 atm with the 25/75 mixture, pumped to a pressure < 0.1 atm, then backfilled with an environment inside the chamber containing ~100% of the sampled gas to 0.5 atm, then 1 atm. The last steps consist of pumping the chamber to < 0.1 atm before being filled with air to 0.5 atm followed by 1 atm. The cylinder gas of CO<sub>2</sub> was nominally 10,000 ppmv in N<sub>2</sub>, CO was 200 ppmv in air, and a 100% dry N<sub>2</sub> gas cylinder was used to displace air in order to measure varying concentrations of ambient O<sub>2</sub> in the testing laboratory. The results are presented in Fig. 6 for the testing of each of these three gases at pressures of 0.5 and 1 atm.

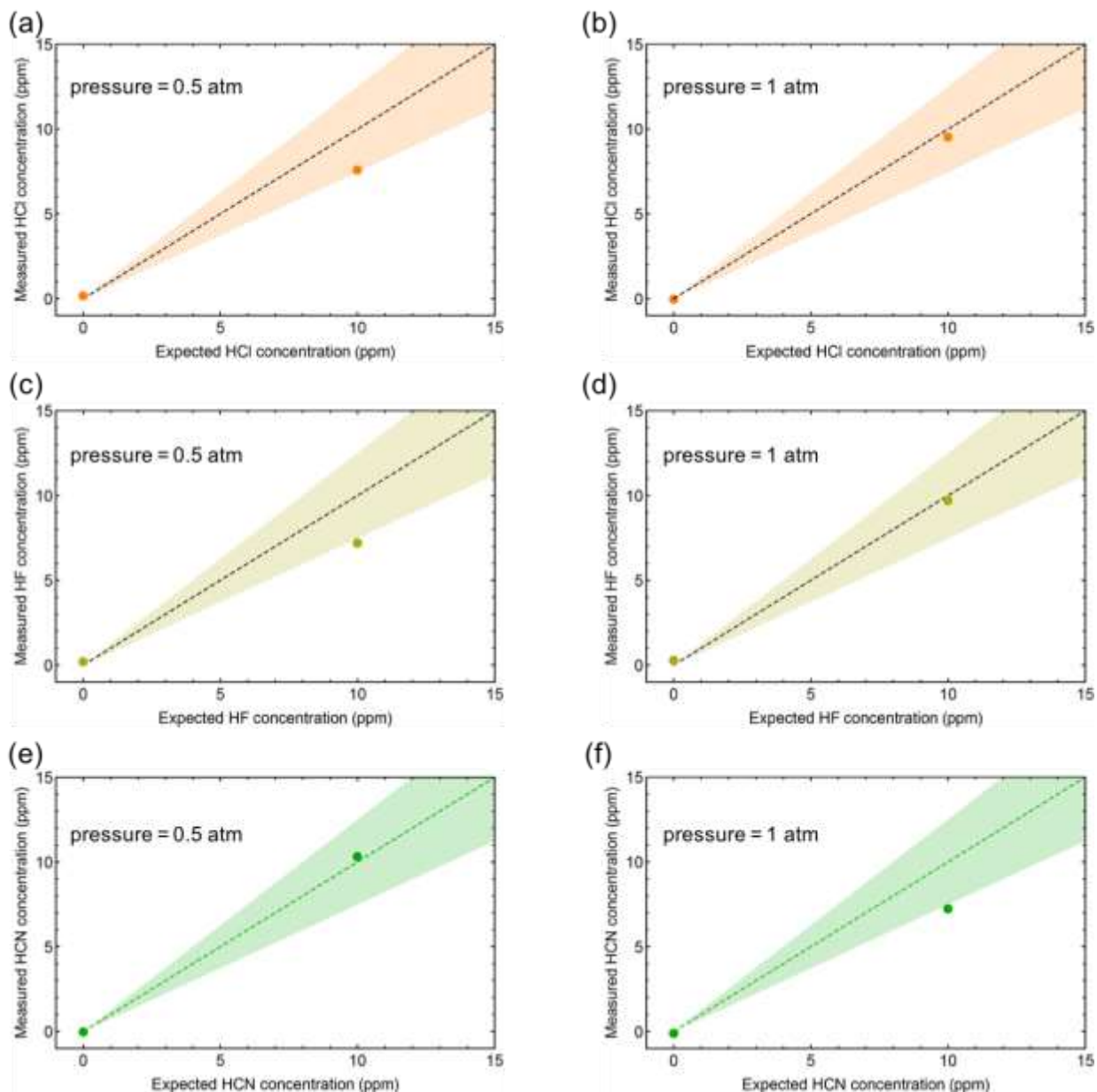
While our targeted minimum concentration of O<sub>2</sub> is 15%, we showed that the sensor can detect down to a few percent of O<sub>2</sub> while remaining accurate within  $\pm 1\%$  absolute O<sub>2</sub>. For both Fig. 6 (a) and (b), the measured concentration of O<sub>2</sub> is on the lower limit of the accuracy requirement for the atmospheric concentration case (~20.9 %). This can be explained with the use of the data collected from the very last steps of the tests, where the chamber was filled with 100% N<sub>2</sub> before being backfilled with air. The remaining presence of N<sub>2</sub> in the chamber might have led us to slightly overestimate the expected value of O<sub>2</sub> concentration. Both CO<sub>2</sub> and CO are found to be well within the requirements throughout the entire test conditions. It is to be noted that the zero-level values for these gases were measured when the chamber was filled with 100% dry N<sub>2</sub>, and that the measured values are well below the minimum detection levels.

Diffusion of the acid gases (HF, HCl, and HCN) from the cylinder to the optical head of the instrument was found to be challenging. This can be attributed to these gases reacting strongly with molecules, such as water, present in the air and on surfaces in the test setup. While this is a known issue, we are solely interested in, and can only detect, molecules present in gaseous form. For the acid gases, we performed tests with the chamber held at either 0.5 atm or 1 atm, and a burst of the gas to be sampled was introduced in the chamber while keeping the pressure constant. The high flows allow for a minimum resident time of these gases in the different gas lines. Figure 7 shows the results of these measurements. Based on these tests, we found that the minimum detection of 2 ppmv is achieved, resulting in the expected detection of the minimum levels accurately. While these channels were not considered as fully calibrated at the moment of these tests, the measured values were nevertheless found to be close to accuracy requirements just from the rough direct-absorption calibrations described above. Also, as explained above, these gases have the tendency to adsorb to surfaces or react with water and other molecules present in the air; therefore, the expected concentrations assumed to be in the optical path of the instrument may be overestimated.

It is also to be noted that sufficiently concentrated smoke can affect our sensor. However, the CPM instrument is intended to operate in an environment with no visible smoke. We are measuring trace amount of gases, with a focus on early fire event detection and evaluation of air quality following a fire event.



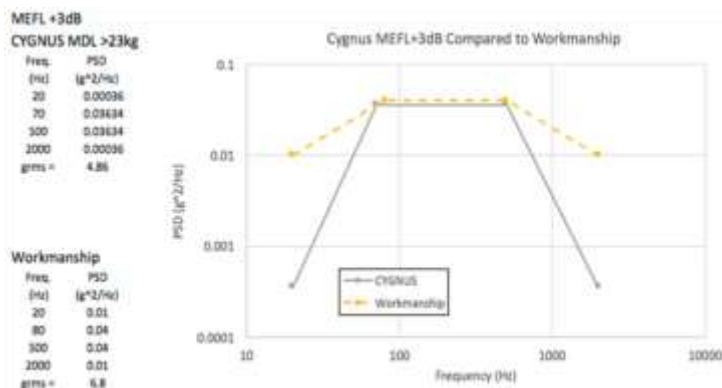
**Figure 6. Results from the testing of the TLAS CPM instrument for  $O_2$ ,  $CO_2$ , and CO. The points represent the measured concentration values of each gas of interest as a function of the expected concentrations at 0.5 and 1 atm. The shaded bands represent the accuracy requirements, which are  $\pm 1\%$  absolute  $O_2$  and  $\pm 10\%$  of the expected level for  $CO_2$  and CO.**



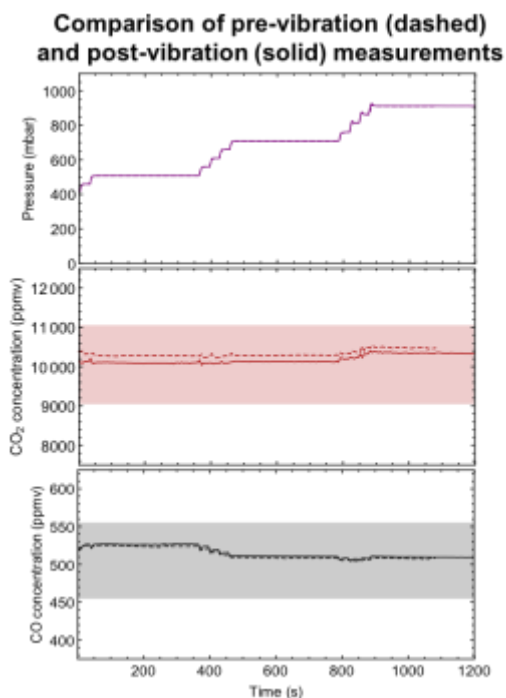
**Figure 7. Results from the testing of the TLAS CPM instrument for HCl, HF, and HCN, prior to final calibration. The circles represent the measured concentration values of each gas of interest as a function of the expected concentrations at 0.5 and 1 atm. The only concentration tested for each gas was 10 ppmv. The shaded bands represent the accuracy requirements, which is  $\pm 25\%$  of expected values.**

Once the CPM instrument was built and tested, a series of vibration tests were performed to ensure proper performances in conditions expected during the Saffire experiment. While the instrument must survive exposure to the CYGNUS vibration levels, we have tested our sensor to the NASA Workmanship levels since the  $g_{rms}$  is higher for the latter, thus giving confidence in the ability of the instrument to support the vibration levels without risking drifts in laser alignment or failure of other components. The vibration levels are shown in Fig. 8. Following these tests, the intensity of the signal at the detector was and the measured gas concentrations for each channel varied negligibly compared to the values before vibrational tests. Figure 9 shows measured levels of  $CO_2$  and  $CO$  over a wide range of

pressure for an expected concentration of 10,000 ppmv and 500 ppmv, respectively, and no significant variations are observed.



**Figure 8. Vibration levels expected aboard the CYGNUS capsule used for the Saffire experiment and NASA Workmanship vibration levels.**



**Figure 9. Comparison of pre- and post-vibration measurements of CO<sub>2</sub> and CO at a concentration of 10,000 ppmv and 500 ppmv respectively over a wide range of pressures. The shaded bands represent the accuracy requirements.**

#### IV. Conclusion

We designed, built, and tested a stand-alone tunable laser absorption-based instrument for combustion product monitoring in a spacecraft environment. The instrument shows response to all six target gases (O<sub>2</sub>, CO<sub>2</sub>, CO, HF, HCl, and HCN) at pressures from 0.5 atm to 1 atm, and the instrument exhibits stable calibration over time and after exposure to realistic levels of random vibration.

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